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(54) Method for direct microstructuring of materials

(57) In a method for direct microstructuring of materials using at least one ultrashort single pulse or a pulse sequence having defined energy input into the material, according to the present invention, to avoid microcracks and strains, at least two temporally formed laser pulses or pulse trains are directed in sequence onto the surface of the material to be processed and the interval of two sequential pulses or pulse trains is set as less than or equal to picoseconds, so that the following pulse is incident in the material to be processed during the change caused by the first pulse, and energy and duration of the pulse are set as a function of the material to be processed.

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[print information]

Description

[0001] The present invention relates to a method for direct microstructuring of materials using at least one ultrashort single pulse or a pulse sequence having defined energy input into the material.
[0002] The direct microstructuring of various materials comprises both, for transparent materials, the modification of the material which results in a change of its optical properties (e.g., transmission change due to index of refraction change or also massive material removal or transformation of the phase of the material) at the irradiated point, and also, for nontransparent materials, a material removal and/or a phase transformation, i.e., transition from one crystal structure into another.
[0003] Up to this point, methods are known from the prior art in which (described, for example, in LaserOpto 31 (3), 91–97 (1999)), the modification is generated on the surface and/or, for transparent materials, in the interior using a single pulse or a pulse sequence of defined number, the pulse intensity being selected in all laser pulse lengths used in such a way that the modification threshold per individual pulse is exceeded. As reported in Phys. Rev. Lett. 74, 2248–2251 (1995), the modification threshold is a function of the duration of the pulses used and the wavelength.
[0004] A method for producing spatial microstructures in transparent materials using laser radiation is described in DE 197 11 049. In this case, with a dimension of the focus of the laser beam to be set on the material surface as a function of the material to be structured, the intensity of the laser pulse is below the threshold for the surface modification and above the critical intensity at which self-focusing begins in the volume, and the deposition of the structured to be generated is set via the pulse length and/or the pulse energy. The method uses the nonlinear optical effect of self-focusing, by which microstructures are generated in the volume of these materials. However, the method is not capable of delimiting structures in the material interior at sizes below 2 μm, because due to the focusing conditions in microstructuring with the aid of self-focusing, the energy input into the material is above the structuring threshold and only single pulses are used.
[0005] If a pulse sequence is used to change the material, the interval of the sequential pulses is at minimum a few nanoseconds, as reported, for example, in CLEO 2000 Technical Digest, CWT4 375–376 (2000) and ibid, CFD3, 580 (2000), but is typically a few tenths of a millisecond up to a few milliseconds, which is a function of the sequence frequency of the laser system used.
[0006] For material changes in the micrometer range, because of the low energy input, laser pulses having a duration of a few tenths of a picoseconds and/or sub-picoseconds are used, as reported in the publication already cited, Phys. Rev. Lett. 74 2248–2251 (1995).
[0007] In solutions for direct microstructuring of materials known according to the prior art, microcracks and strains occur, which reduce the quality of the desired structuring.
[0008] It is therefore the object of the present invention to specify a method for direct microstructuring of materials in which the cited disadvantages are avoided.
[0009] The object is achieved by a method of the type cited at the beginning in that, according to the present invention, at least two temporally shaped laser pulses or pulse trains are directed in sequence onto the surface of the material to be processed and the interval of two sequential pulses or pulse trains is set as less than or equal to picoseconds, so that the following pulse is incident in the material to be processed during the change caused by the first pulse, and energy and duration of the pulse are set as a function of the material to be processed.
[0010] The method according to the present invention, in which the energy fed into the material to be processed is distributed onto multiple pulses, allows influencing of the primary process, which occurs in a very short time, by varying the relative intensity and pulse duration of the individual sequential pulses and their temporal interval from one another. Exploitation of the primary process which occurs in every material after the action of an intensive laser pulse is thus possible. These laser pulses are understood, for example, as the excitation of a large number of electrons from the valence band into the conduction band in transparent materials (as described, for example, in Nucl. Instr. Phys. Res. B 116, 43-48 (1996)), so that the state of the transparent material becomes similar to metal. In this metal-like state, the otherwise transparent, brittle, and fragile material becomes ductile for a very short time (for the duration of sub-picoseconds), i.e., it becomes tough like a metal. The material may now be processed using a following laser pulse of suitable duration and intensity in such a way that cracks and strains are avoided in the material. If the primary processes caused by the first laser pulse have faded away, the material returns into its original state, but it is now modified in the desired way at the irradiated point. Strains and cracks as occur in the event of individual laser pulses or laser pulse trains having nanosecond or greater intervals due to the material brittleness, are avoided in the method according to the present invention.
[0011] In an embodiment according to the present invention, the energy of each single pulse is below the microstructuring threshold (this is the minimal energy

at which a change of the material—as described at the beginning—occurs) and only the sum of all pulses is above this threshold, so that a very careful input into the material to be processed occurs, because of which—as already noted—the occurrence of strains and cracks is minimized. The requirement for this is that in each case the following pulse still "feels" something of the preceding pulse. This is only the case at a time scale of sub-picoseconds or picoseconds.

[0012] Because of the short pulse durations and the small time intervals between the individual pulses in the method according to the present invention, excitation in very short-lived unstable intermediate states is possible. If a following pulse is incident precisely in this state, a new state may be reached by its excitation, which may not be activated directly (using only one laser pulse).

[0013] In an embodiment of the present invention, the energy and duration of the sequential temporally shaped pulses are to be set differently and thus specific conditions are made possible for various materials.

[0014] In another embodiment, a wavelength which is arbitrary is set as a function of the material to be processed for each individual pulse.

[0015] For microstructuring quartz glass, two laser pulses are focused onto the surface of the material to be processed whose pulse interval is 0.6 ps and whose pulse duration is 0.2 ps each.

[0016] For microstructuring graphite, in a further embodiment, at least two laser pulses are used whose pulse length is less than 0.2 ps and whose interval is less than or equal to 2 ps, a phase transformation of the graphite structure into a diamond structure being generated.

[0017] In the method according to the present invention, the ultrashort laser pulses, whose interval of two sequential pulses is set to less than or equal two picoseconds, are generated using the pulse-shaping methods in a short pulse laser, preferably a CPA (chirped pulse amplification) laser system (described, for example, in Optics Letters, Vol. 23, No. 20, October 15, 1998, 1612–1614), as provided in another embodiment.

[0018] As a result of the method according to the present invention for direct microstructuring of materials, these changes may be permanent or also impermanent. The method according to the present invention does not require any (chemical) postprocessing of the structure change achieved.

[0019] Further embodiments of the present invention are specified in the subclaims and in the following exemplary embodiment, which is explained in greater detail on the basis of figures.

[0020] Figure 1 shows a microscope image of the result of a modification of quartz glass in a top view and side view using a single pulse, whose curve is shown underneath, Figure 2 shows a microscope image of the corresponding views of the modification using a double pulse.

[0021] To modify a quartz glass disk according to the prior art, it is irradiated using a pulse of a Ti-sapphire laser, which has a fundamental wavelength of 800 nm. The pulse duration of this single pulse is 0.2 ps, its intensity is approximately 80 J/cm². Filamentation of the channel is recognizable in the side view in Figure 1. This is avoided in the event of modification using a double pulse according to the method according to the present invention using the above-mentioned laser, whose pulse length, phase, and amplitude are variable. The result is recognizable in Figure 2. The two pulses are directed at an interval of approximately 0.6 ps onto the quartz glass disk. The total energy is identical to that specified for Figure 1. Cracks may be seen on the left side of the microscope image in Figure 1, these no longer occur in the event of microstructuring using a double pulse.

Patent Claims

1. A method for direct microstructuring of materials using at least one ultrashort single pulse or a pulse sequence having defined energy input into the material, **characterized in that** at least two temporally shaped laser pulses or pulse trains are directed in sequence onto the surface of the material to be processed and the interval of two sequential pulses or pulse trains is set as less than or equal to picoseconds, so that the following pulse is incident in the material to be processed during the change caused by the first pulse, and energy and duration of the pulse are set as a function of the material to be processed.

2. The method according to Claim 1, **characterized in that** energy and duration of the sequential temporally shaped pulses are set differently.

3. The method according to Claim 1, **characterized in that,** in addition, an arbitrary wavelength is set for each single pulse as a function of the material to be processed.

4. The method according to Claim 1, **characterized in that** the energy of each single pulse lies below the microstructuring threshold and the sum of all pulses lies above this threshold.

5. The method according to Claim 1, **characterized in that** the ultrashort temporally shaped laser pulses, whose interval of two sequential pulses is set to less than or equal to picoseconds, are generated using the pulse shaping methods in a short pulse laser, preferably a CPA (chirped pulse amplification) laser system.

6. The method according to Claim 1, **characterized in that**, for the microstructuring of quartz glass, two laser pulses are focused onto the surface, whose pulse interval is 0.6 ps and whose pulse duration is 0.2 ps each.

7. The method according to Claim 1, **characterized in that**, for the microstructuring of graphite, at least two laser pulses are used, whose pulse length is less than 0.2 ps and whose interval is less than or equal to 2 ps, a phase transformation of the graphite structure into a diamond structure being generated.

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